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RSIC-481

EXPLODING FOIL TECHNIQUES: A BIBLIOGRAPHY

by
Herbert H. Hoop

October 1965

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ABSTRACT

This bibliography of "Exploding Foil Techniques" is an attempt to furnish basic exploding conductor information, and to locate literature on operating exploding foil systems, energy storage systems, design of power supplies, and fast energy release systems. The listed documentation describes the use of exploding foil and films to produce hypervelocity plasmas, to accelerate particles, to create shock waves in matter, to create intense light pulses, and to compress magnetic fields. A number of pulse power energy storage systems are described.

FOREWORD

This bibliography of "Exploding Foil Techniques" was made at the request of the Missile Design Branch, Structures and Mechanics Laboratory, Research and Development Directorate, U. S. Army Missile Command. Of special interest was foil dimensions, foil materials, components of power supplies, low inductance energy storage systems, and pressure pulse output resulting from exploding foils.

The primary sources searched are as follows:

1) RSIC document card file
2) Defense Documentation Center abstract bulletins and bibliographic service
3) NASA tape search which references International Aerospace Abstracts and Scientific Technical Aerospace Reports
4) Applied Science and Technical Index
5) The Engineering Index
6) Index Aeronauticus
7) Nuclear Science Abstracts
8) Science Abstracts (PHYSICS)

CONTENTS

Section I. INTRODUCTION

A newcomer in the general field of exploding conductors is the exploding metal foil. The bulk of documentation on exploding conductors is centered around the exploding wire. The first paper on exploding wires was read before the Royal Society of London in 1773. From that date to 1950 the data on the exploded conductor was accumulated at a slow rate. Since then the data has accumulated at an accelerated pace.

Exploding conductors are used to ignite ordnance devices, to create sources of high heat and light intensity, to create intense shock waves in matter, and to generate high energy, dense plasmas. Exploding foils have been used to bond materials, coat materials, to accelerate small particles to hypervelocities to compress magnetic fields, and could possibly be used in a propulsion device where slight corrective power pulses are needed.[11, [illegible], 22]

Certain wire configurations could possibly be used in a similar manner. Whatever the application or shapes of the conductor, the electrical circuit components are similar and perform similar functions, the only difference being in size and characteristics. Each circuit contains an energy storage device, a switch or triggering device, and an explosive conductor.

The energy storage device may be a bank of very large capacitors with a total capacity up to 100 microfarads, and may be charged up to 10 to 100 kilovolts. Current peak flow from the bank may be 100,000 to 200,000 amperes. The energy may be from 1 to 100,000 joules.

This high rate of energy release requires special switch devices and transmission lines.[13, 22, 26] The switching device may be a triggered spark gap or electronic tube such as an ignitron or thyratron. An effort is usually made to match the impedance of the transmission line with that of the exploding conductor.

Most data related to exploding wires would be useful in understanding the problems and phenomenon of exploding foils and films. Some differences have been observed in the behavior of exploding wire, foil, and films. The characteristics of the exploding foil would be somewhat similar to the exploding wire and exploding film. Current-time traces indicate a two-step discharge phenomenon similar to the one observed with exploding films.[29]

The folding process, which is attributed to thermal expansions aided by magnetic forces, is evident in foil studies. The folds look like accordion pleats and are aligned perpendicular to the nominal current path. In the case of exploding films, the perpendicular striations were also attributed to thermal and magnetic expansion away from the substrate. Thicker films produce higher first current pulse and the second current pulse decreases with film thickness. At the instant a wire is connected to the capacitor, current begins to flow through the wire with a rise time of less than a microsecond. Because of the skin effect, the current is initially confined to the surface of the wire and reaches the center after some small but finite time.[5,18] A wire or thick foil would be surrounded by a liquid film before breaking up. This effect would not be noticeable before a film explodes.

The most extensive research related to exploding foils has gone into the development of an exploding foil gun which accelerates thin-plate projectiles to hypervelocities.[11,23,24] This work has been accomplished by the Boeing Company, the Air Force Special Weapons Center, and by Technical Operations Research under Contract AF 33(616)-8423 for the Air Force Materials Laboratory.

A comparison of operating energy storage systems may be made by studying these research systems. The state-of-the-art in high power energy storage systems, such as capacitor, electro-chemical pulse systems and dynamic pulse systems, are exhibited in these systems and those discussed at the, "Proceedings of the IDA Pulse-Power Conference 4-5 February 1963."[20]

The difference in the resistance of metal films at ambient temperature and at the melting point may vary greatly for different metals. Copper shows the greatest increase for several films tested. Increases in film thickness does not appear to effect the discharge characteristics as greatly as voltage increases.[28] A higher first current pulse in thicker films is caused by a slower heating rate (lower amperes per square centimeter). A comparison of the behavior of exploding tungsten and molybdenum, 0.040 x 0.0003 inch, foil ribbons with 1.5 kilovolts on 2 microfarad condensors shows a difference in the current versus time traces and in the particle separation.[29] This is attributed to the difference in the boiling points of the two metals.

A pulsed plasma accelerator employing continuously fed thin metal films as a plasma source has been developed.[26] An alloy of cadmium and zinc has been found to be a satisfactory propellant. Films appear to be more suitable for propulsion because of greater directionality. Quantities of energy several times that required for vaporization may be placed in a film during the initial conduction phase.

The magnitude of a pressure pulse produced by an exploding conductor would be a function of the rate of energy release. Increasing the stored energy or voltage does not necessarily increase the current rise because higher voltage capacitors require more insulation spacing, and inductance is increased. Some information is offered on this problem by the Air Force Weapons Laboratory and the University of Michigan, Department of Electrical Engineering, and the Lewis Research Center, NASA.[9,14,15] Foil materials may be exploded by methods other than the release of energy by the conduction of electricity. This may be accomplished by the use of concentrated light energy or by charged particle beams.[10,25]

High energy explosive foil ribbon systems, 20 kilojoules to 100 kilojoules, have been used mainly in hypervelocity guns.[11,13,24,27] The storage capicators may be charged from 10 kilovolts to 125 kilovolts. In these guns, foil thickness has ranged from 0.0001 to 0.002 inch. The length and width may vary from 0.1 to 2 inches. Aluminum foil has been the main explosive material used. In one lower energy system, (10 kilovolts, 1 kilojoule), exploding silver cylinders, 1 to 20 microns thick, were used to compress a magnetic field. Some explosive foil and film systems (1 kilovolt to 9 kilovolt, 1 kilojoule to 3 kilojoules). have used tantalum, brass, tungsten, thoriated tungsten, molybdenum, iron, nickel, aluminum, silver, tin, brass, and copper as the explosive.[22,28,29,30]

Some variation in material, material dimensions, and voltage was used in these tests, but the range in variables was not sufficient to determine the optimum power supply and other components needed to explode a conductor. Some further research is needed to extend the range of these variables. An optimum metallic plasma accelerator would require high voltage, appreciable capacitance, and very low inductance and radiating areas.[26]

Section II. SELECTED BIBLIOGRAPHY

1. Aerospace Information Division, Washington, D. C., EXPLODING WIRES, FILMS, AND RIBBONS, ANNOTATED BIBLIOGRAPHY, 3 June 1963, AD-406 244. (Unclassified report)

This bibliography is intended as a guide to Soviet literature on electrically exploded conductors. It was compiled from six Soviet journals, spanning the period March 1957 to January 1963. The eleven entries are arranged alphabetically by author. An annotation is provided for each article.

2. Air Force Cambridge Research Laboratories, Bedford, Massachusetts, A BIBLIOGRAPHY OF THE ELECTRICALLY EXPLODED CONDUCTOR PHENOMENON, SUPPLEMENT NO. 1 by W. G. Chace and E. M. Watson, June 1965, AD-618 131, Project No. 8608, Task No. 860804. (Unclassified report)

Not abstracted.

3. Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio, DEVELOPMENT OF A RESEARCH CAPABILITY FOR ACCELERATING HYPERVELOCITY PARTICLES by R. W. O'Neil, and V. E. Scherrer, 30 October 1964, Report No. AFML-TR-64-333, Contract No. AF 33(657)-10316, Project No. 7360, Task No. 736006. (Unclassified report)

Technical Operations Research has developed and installed a hypervelocity facility at the Air Force Materials Laboratory for accelerating small particles to meteoric velocities for simulating the effects of micrometeoroid impact on materials. The particles are accelerated by discharging an electronically-triggered, high-energy capacitor storage system into an exploding-foil gun. High-speed streak and framing cameras measure particle velocity, size, shape, and momentum. Electronic instrumentation is provided to measure capacitor bank discharge characteristics and energy input to the exploding-foil gun. Particles

have thus far been accelerated in this facility to velocities greater than 4C,000 feet per second.

4. Author unknown.
   METALLIC VAPOR PLASMA: FUTURE PROPELLANT? Electronics, pp. 20-21, 18 August 1961.

   Groundwork for future plasma pulsed propulsion systems is being readied at Electro-Optical Systems, Incorporated, Pasadena, California. Being performed for the Office of Aerospace Research, the work so far has consisted of preliminary experiments producing relatively large amounts of metallic vapor plasma by electrically exploding metallic wires and thin metallic films. High temperature expansion of the plasma has resulted in measurable thrust that may have future propulsion applications.

5. Bolotovsky, B. M.,
   SKIN EFFECT IN THIN FILMS AND WIRES, Zhural eksperimental'noy i teoreticheskoy fiziki, Vol. 32, No. 3, pp. 559-565, 1957, (In Russian).

   Impedances of thin films and wires and the application of the kinetic theory to thin conductors are studied. A thin conductor means a conductor whose thickness is much less than the free path of an electron in an infinite metal space. By using the Chambers method (1950), differential and integral equations pertaining to the skin effects are derived, and, after certain simplifying conditions are postulated, and solved. The solution of the equations show that: (1) the ratio l/b is the fundamental parameter under the condition of a conductive semispace, where l is free path length and b is the classical skinlayer depth; (2) the ratios of wire radii and film thicknesses to field penetration depths are the critical parameters in dealing with thin conductors; and (3) when a conductor cannot be assumed thin and the anomalous skin effect takes place, the conductor impedances can be determined by utilizing approximate solutions.

6. Clark, W. H., Hopkins, A. K., Myrberg, J. E., O'Neil, R. W., Scherrer, V. E. and Stevens, H. C.,
AMFL EXPLODING FOIL GUN, DEVELOPMENT, DIAGNOSTICS, DATA, Proceedings of the Seventh Hypervelocity Impact Symposium, Tampa, Florida, 17, 18, 19 November 1964. Vol. I. Techniques., 364 pp., February 1965, AD-463 227.

An exploding foil particle accelerator facility is being used at the Air Force Materials Laboratory to study hypervelocity impact phenomena. A 50,000 joule capacitor bank is used as the energy source to explode an aluminum foil. The combined effect of the foil explosion and the magnetic essure on the plasma is used to accelerate particle with masses of a few milligrams to velocities as high as .2.5 kilometers per second.

7. Comitato Nazionale per l'Energia Nucleare, Frascati (Italy), Laboratorio Gas Ionizzati,
COMPRESSION OF MAGNETIC FIELD BY EXPLODING FOILS by J. G. Linhart and G. Schenk, May 1964, Report No. LGI-64/7. (Unclassified report)

Experiments are described in which a thin cylindrical metalic foil is exploded passing a pulse of electrical current through it. The plasma generated in such an explosion compresses an axial magnetic field. Initial fields of several kilogauss were thus compressed to about 50 kilograms. Interpretation of the details of the explosion and compression processes is attempted.

8. Deutsch, F.,
SWITCHES FOR HIGH-CURRENT PULSES AT HIGH VOLTAGES, (Schalter für Hochstromimpulse bei hohen Spannungen), Association Suisse Des Electriciens Bulletin, Vol. 55, No. 22, pp. 1123-1129, 31 October 1964. (In German)(Unclassified report)

Turning-off and -on (switching) of accumulators (electric storage units) and their quick discharge make great demands on the switch. The qualities that a switch must have for these purposes are defined. The suitability of spark gaps, controlled spark gaps, thyratrons, and ignitrons for high-

current switching is reviewed. Break-down potential, Switching capacity, and ignition delay of the different elements are discussed.

9. Early, H. C. and Martin, F. J.,
METHODS OF PRODUCING A FAST CURRENT RISE FROM ENERGY STORAGE CAPACITATORS, The Review of Scientific Instruments, Vol. 36, No. 7, pp. 1000-1002, July 1965.

A rate of current rise cf the order of 10^{13} A sec^{-1} can be produced by inexpensive capacitors used in conjunction with a special, low inductance fuse and spark gap. The capacitors are discharged through the fuse until the current reaches a near maximum value at which time the current is transferred from the fuse into a load inductance of about lnH. The spark gap isolates the load until the moment of current transfer.

10. Eitel-McCollough, Incorporated,
PULSE HEATING OF MATERIALS BY HIGHLY CONCENTRATED ELECTRONIC BEAMS by O. Heil and S. Vogel, January 1962, Report No. AFCRL-62-167, Air Force Research Laboratories, Bedford, Massachusetts, Contract No. AF 19 (604)-8810, Project No. 4610. (Unclassified report)

Electron bombardment provides a means of heating with high local energy concentration and definition. The object of this study is to investigate surface explosions and structural changes of matter caused by high temperatures, large temperature gradients, and fast quenching rates connected with electron bombardment. It is intended to operate close to the absolute limits of energy concentration in electron beams.

11. Guenther, A. H., Wunsch, D. C. and Soapes, T. D., ACCELERATION OF THIN PLATES BY EXPLODING FOIL TECHNIQUES, Proceedings of the Second Conference on the Exploding Wire Phenomenon, Boston, Massachusetts, 13-15 November 1961, Vol. 2, Exploding Wires, pp. 279-298.

A technique for the acceleration of thin plates to high velocities by exploding foils has been developed. These plates, primarily Mylar and Lucite up to 3 by 3 inches and from a few mils to ¼-inch thick, are used to produce high-impulse, short-time loading of materials for the purpose of material dynamics at high pressures. Velocities up to $5 . 10^5$ centimeters per second have been achieved. A brief description of equipment including the capacitor system, cameras, and back-lighting, etc., is given, as well as a more detailed description of the construction of the transducer and its characteristics. Methods of velocity determination are described. High-speed photographs of these high-velocity plates are presented.

12. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, THE EXPLODING WIRE PHENOMENON (REVISION) by C. A. Privette, 10 April 1963, Report No NASA-CR-50 728, JPL-TM-33-113, NASA Contract No. NAS7-100. (Unclassified report)

A brief outline of the exploding-wire phenomenon, together with a description of some techniques employed in measuring various parameters of the explosion process is presented. Two copper wires, 1 and 3 mil in diameter, were exploded, utilizing a 16,000-joule capacitor bank. These explosions are used as models for various theoretical descriptions concerning temperature and current histories. Results of these theoretical treatments predict maximum temperatures of approximately 100,000°C and maximum currents of 10,000 amperes.

13. Keller, D. V. and Penning, J. R. Jr.,
EXPLODING FOILS-THE PRODUCTION OF PLANE SHOCK WAVES AND THE ACCELERATION OF THIN PLATES, Proceedings of the Second Conference on the Exploding Wire Phenomenon, Boston, Massachusetts, 13-15 November 1961, pp. 263-277.

The electrical explosion of thin metal foils has been used to induce shock waves in solids. The foil is either placed in direct contact with the solid, or is used to accelerate a thin-plate projectile to high velocity before it strikes a target. Pressures up to 10 kilobars are readily obtainable with the direct-contact method. Using the second method, we have accelerated 2 inch-Mylar plates to over 0.4 centimeter per microsecond, resulting in pressures over 80 kilobars. The deviation from planarity of the shock waves produced by the two methods is approximately the same and is due to a slight nonsimultaneity in the foil explosion. Typically, a 2-inch square thin aluminum foil explodes simultaneously over its area within about 10^{-7} seconds. This excellent simultaneity permits the acceleration of very thin projectile plates, with resultant short-duration pulses. We have used 5-mil Mylar projectiles which produced 80-kilobar pulses with durations of only about 0.1 microsecond. The dependence of the pressures and velocities obtained upon the circuit and foil-load assembly parameters will be discussed.

14. Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio,
CHARACTERISTICS OF A 5-KILOJOULE, IGNITRON-SWITCHED, FAST-CAPACITOR BANK by C. J. Michels and F. F. Terdan, Washington, NASA, May 1965, Report No. NASA-TN-D-2808, 22 pp. (Unclassified report)

The electrical characteristics of the bank are a capacitance of 12.1 microfarads, an inductance of 14 nanohenries, a voltage range of 10 to 30 kilovolts, and a resistance of 0.0038 ohm. The bank consists of 11 identical capacitor sections, each synchronously switched with an ignitron. All components hold off voltage to 30 kilovolts for an automatic fast charging mode of operation after a laborious conditioning process. A slower ½-minute charging time for manual charging mode limits reliable operation to 25 kilovolts only. Synchronization to within tens of nanoseconds

is obtained through the use of a fast, high-voltage trigger signal and ignitron temperature control. Typical transient current and voltage traces, as well as the instantaneous power plots obtained from these traces, are described for each component of one section of the bank with a 150-nanohenry load. Instrumentation, including the adaptation of a commercial voltage probe, used in an off-ground high-noise area, is also described.

15. Los Alamos Scientific Laboratory, New Mexico,
THE POWER CROWBAR ENERGY SYSTEM FOR SCYLLA IV by E. L. Kemp and W. E. Quinn, 10 March 1965, Report No. LA 3189-MS, Contract No. W-7405-ENG-36, 23 pp. (Unclassified report)

The energy storage system of Scylia IV has four capacitor banks, which are applied in the following order: (1) the reverse bias bank--10 kilovolts, 280 kilojoules, with a rise time of 60 microseconds; (2) the preionization bank--40 kilovolts, 9 kilojoules that rings at 300 kilocycles per second; (3) the primary bank--50 kilovolts, 540 kilojoules with a rise time of 3.7 microseconds; and (4) the power crowbar bank--20 kilovolts, 3 MJ with a rise time of 25 microseconds. The switch of the fourth bank must hold off the pulse voltages applied by the other three banks while also holding off the dc voltage of the power crowbar bank. It must also fire with low jitter when the voltage across it is near zero. Three types of switches for this application are discussed: a 20 kilovolt ignitron, a developmental 50 kilovolt ignitron, and a vacuum spark gap. Various methods of triggering the preferred vacuum switch are presented. A washer gun, chosen as the trigger for each gap, is discussed. The 3 MJ capacitor bank is examined as a system which includes the capacitor protection scheme, the prefire protection circuit, and the complete firing system.

16. Martin Company, Orlando, Florida,
EXPLODING BRIDGEWIRE SYSTEMS REPORT, February 1965, Report No. OR 6383, Contract No. DA-01-021-AMC-11437 (Z). (Unclassified report)

This report represents a practical approach to the analytical development of exploding bridgewire systems. It combines the results of a linear and non-linear analysis with empirical laboratory data to yield a design procedure.

This design procedure is intended to be an aid in the design of future EBW systems. The commonly observed phenomena of EBW are described, and methods of optimizing these phenomena from a systems standpoint are specified. In addition, this report includes numerous curves and data obtained from the PERSHING EBW system, with special references to the PERSHING EBW firing unit and cable tester.

17. Martin Company, Orlando, Florida,
RELIABILITY DESIGN ANALYSIS OF THE PERSHING MODULAR EXPLODING BRIDGEWIRE SYSTEM, October 1962, Report No. OR 2856, Contract No. DA-01-009-ORD-634. (Unclassified report).

This report consists of a design analysis and a failure mode analysis of the modular EBW system being developed under STAD 10-74.

18. Manninger, R. C.,
RADIAL DISTRIBUTION OF CURRENT AND ITS EFFECT IN AN EXPLODING WIRE, Conference on the Exploding Wire Phenomenon, April 1959, pp. 156-163.

An analysis of short duration currents in a wire shows that the skin effect can cause a time-dependent radial distribution of current in the wire. The problem is one of determining proper boundary conditions and of obtaining transient solutions for the diffusion equation with current density as the dependent variable. The effects of the current distribution on exploding wire phenomena are discussed.

19. Physics Laboratory, Directorate of Materials, Aeronautical Systems Divisions, Wright-Patterson Air Force Base, Ohio,
EFFECTS OF HYPERVELOCITY IMPACTS ON MATERIALS by V. E. Scherrer, August 1962, Report No. ASD-TDR-62-762, Contract No. AF 33(616)-8423, ASFC Project No. 7360, Task No. 736003, 93 pp. (Unclassified report)

A novel exploding-foil gun is described which routinely accelerates small particles (mass 1-100 milligram) to velocities up to 60,000 feet per second when coupled to a slow capacitor energy storage system. When the gun was efficiently coupled to a fast-capacitor energy storage system,

a single, solid particle was accelerated to a velocity of 102,000 feet per second. A detailed study of various particles impacting quasi-infinite lead targets was made, and preliminary results are given for particle velocities from 7,000 to 40,000 feet per second. These results indicate a deep penetration phenomenon for a particle velocity of 15,000 feet per second. If similar phenomena are observed in materials of interest in space vehicle construction, the results will be very important in the design of such structures. Plans are presented for expanding the hypervelocity facility and improving its performance in the future.

20. Research and Engineering Support Division, Institute for Defense Analyses, Washington, D. C.,
CAPACITOR ENERGY STORAGE, ELECTROCHEMICAL PULSE SYSTEMS, AND DYNAMIC PULSE SYSTEMS, Proceedings of the IDA Pulse-Power Conference, 4-5 February 1963, Vol. IV, Study S-104, July 1963, Report No. ARPA SD-50, Report No. IDA/HQ-63-1415, Report No. AD-434 752, 152 pp. (Unclassified report)

Contents:

11. LEAD ACID BATTERIES by H. E. Zahn, pp. 76-77.
12. K-Hg LIQUID METAL CELLS by R. E. Henderson, pp. 78-82.
13. PRELIMINARY REVIEW OF AN AMALGAM FUEL CELL by J. S. Smatko, pp. 83-88.
14. ENERGY AND HIGH PULSE GENERATION by W. Wright and L. A. Kilgore, pp. 89-96.
15. ENERGY GENERATION OR LONG DURATION STORAGE BY DYNAMIC METHODS by L. A. Kilgore, W. Wright, and C. H. Church, pp. 97-98.
16. PROPOSALS FOR THE GENERATION OF HIGH ENERGY PULSES by C. H. Church, pp. 99-100.
17. SUMMARY OF COMMENTS ON 100,000 KW GAS TURBINE-GENERATOR by C. E. Kilbourne, pp. 101-104.
18. MOTOR-GENERATORS AND HIGH MAGNETIC FIELDS by C. G. Adams, pp. 105-119.
19. ELECTROMECHANICAL PULSERS by E. Levi, pp. 120-141.

21. Schenk, G. and Lindhart, J. G.,
COMPRESSION OF MAGNETIC FIELDS BY EXPLODING FOILS, Proceedings of the Third Conference on the Exploding Wire Phenomenon, Boston, Massachusetts, 10-12 March 1964, pp. 223-230.

Experiments are described in which a thin cylindrical metallic foil is exploded by passing a pulse of electrical current through it. The plasma generated in such an explosion compresses an axial magnetic field. Initial fields of several kilogauss have been thus compressed to about 60 kilogauss. Interpretation of the details of the explosion and compression processes is attempted.

22. Schiff, D.,
BONDING EXPERIMENTS WITH EXPLODING FOILS, Conference on the Exploding Wire Phenomenon, April 1959, pp. 283-287.

A 2500-joule, 8000-volt condenser bank was used with a spark gap trigger circuit in a series of experiments on exploding wires and foils and their application to coating and bonding. The most interesting result was the bonding of quartz. Two pieces of $^3/_8$-inch-diameter quartz rod were

clamped so that their flat, polished ends butted against one another with a 1-milliradian-thick tantalum foil in between. The tantalum foil formed the high resistance part of the electrical circuit and was vaporized when the condenser bank was discharged. That part of the foil pressed between the quartz rod acted as a weld or bonding agent. The bonded section had a tensile strength greater than 2000 psi.

23. Technical Operations Research, Burlington, Massachusetts, EFFECT OF HYPERVELOCITY IMPACTS ON MATERIALS by R. W. O'Neil, S. Holland, T. Holland, V. E. Scherrer and H. Stevens, January 1965, Report No. AFML-TR-65-14, AD-610 864, Contract No. AF 33(615)-1333, p. 98. (Unclassified report)

The exploding-foil hypervelocity particle-acceleration technique is described. The dependence of the technique on specific geometrical factors in the gun and on discharge characteristics of the electrical storage system is reported. A semi-quantitative theory for predicting the magnitude and time dependence of the most significant operative mechanisms was conceived for the exploding-foil gun. The program was divided into two phases. In the first phase of the work, techniques were devised to measure accurately the parameters affecting particle acceleration. The second phase investigated the performance of a standardized gun model chosen for this study as a function of stored electrical energy and of actual input power. Good correlation was found to exist between particle velocity and power input rate. Preliminary measurements were made on the impacting mass at several energies in the experimental series. The feasibility of accelerating spherical particles with exploding-conductor technique was discussed.

24. Technical Operations Research, Burlington, Massachusetts, EFFECTS OF HYPERVELOCITY IMPACTS ON MATERIALS by V. E. Scherrer, M. Beran, H. Stevens, and R. W. O'Neil, June 1964, Report No. ML-TDR-64-161, AD-601 880, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, Contract No. AF 33(616)-8423. (Unclassified report).

Reliable diagnostic techniques were developed to measure the mass and velocity of hypervelocity particles projected

by an exploding-foil gun. Velocities were increased from 20,000 feet per second to better than 35,000 feet per second as a result of improved gun design and modifications to the energy storage system, including the installation of an electrically triggered switching system. The electro-optical 6-frame Kerr cell camera was also evaluated. A program to measure the electrical parameters of the system and to correlate them with photographic data was instituted, and a theoretical model for the partition of impact energy of a hypervelocity particle was begun.

25. Technical Operations, Incorporated, Burlington, Massachusetts, ELECTRON BEAM SIMULATION OF X-RAY EFFECTS IN MATERIALS (U) by P. Kafalas, A. Melhorn, and I. L. Kofsky, October 1963, Report No. TO B63 64, Report No. RTD-TDR63 3058, AD-345 337, Contract No. AF 29(601)-4558, Project No. 5776, Task No. 577601, 90 pp. (Secret report)

The deposition of the energy of an electron beam in a target was studied by a calorimetric technique. Reliable dose-vs-depth data can be obtained by this means. This technique was applied to determine energy deposited in stacked-foil targets subjected to high flux (greater than 100 calorie per square centimeter) and low-flux (less than 20 calorie per square centimeter) irradiations. Observable effects were produced in some special point samples subjected to low-flux irradiations. Spectroscopic studies of the vaporized front surface of a target subjected to a high-flux irradiation revealed the existence of highly excited and highly ionized species in the vapor. These species exist for about 10 to -6th power seconds which is much longer than the measured time for energy deposition. In all, 78 spectral lines were identified in the vapor.

26. Trolan, J. K., Charbonnier, F. M., Collins, F. M., and Guenther, A. H., VERSATILE ULTRAFAST PULSED POWER SYSTEM, Proceedings of the Third Conference on the Exploding Wire Phenomenon, Boston, Massachusetts, 10-12 March 1964, pp. 361-387.

A unique pulse power system has been constructed to generate very high-energy-density plasmas for the specific purpose of determining the electrical, thermodynamic, and

radiative properties of materials at high temperatures. Theoretical considerations indicate that, if a sufficiently fast rate of energy transfer is achieved, the very high temperature can be obtained even though there is only moderate stored energy ($\sim 10^3$ joule) in the system. Therefore the system has been designed to provide a very fast rising pulse (< 8 nanoseconds) of short duration (~ 50 nanoseconds) for the condition of a constant and matched 4.7-ohm load impedance. System design features to be discussed include the paralleling of 15 synchronized 320-kilovolt Marx surge generators coupled to an evacuable transducer chamber by means of a multiple-input matched impedance transmission line.

Special care was given to the development of reliable electrical and optical diagnostic instrumentation and of a set of operational system checks. Results based on preliminary testing of the recently completed pulser will be discussed.

27. Utah Research and Development Company, Incorporated, Salt Lake City, Utah,
HYPERVELOCITY GUNS USING A CAPACITIVE ENERGY SOURCE by J. E. Myrberg and W. H. Clark, June 1965, Report No. AFML-TR-65-200, Air Force Materials Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Contract No. AF 33(615)-1251. (Unclassified report)

This study is concerned with the development of hypervelocity particle accelerators using a 50,000 joule, 40 microfarad capacitor bank as an energy source. Two types of accelerators have been used successfully. The first of these is the exploding-foil gun. This gun accelerates a thin mylar disk by the expansion of the hot gases produced in the explosion of an aluminum foil. By properly arranging the return current lead, a substantial increase in the velocity can be obtained from magnetic forces. This gun has been fired at velocities up to 12 kilometers per second. Five-milligram mylar disks are routinely being fired to test space structures at 8.0 kilometers per second. The second type of accelerator is the coaxial gun. A plasma is accelerated in the coaxial section by magnetic forces, and the projectile is accelerated by momentum transfer from the plasma. Velocities in excess of 15 kilometers

per second have been obtained using this gun. Other types of guns which have been used with little success are reported; these are rail guns, repulsion-coil guns, and gas guns.

28. Woffinden, G. J.,
EXPLODING METAL FILMS, Proceedings of the Third Conference on the Exploding Wire Pheromenon, Boston, Massachusetts, 10-12 March 1964, pp. 193-210.

Vacuum evaporated films of aluminum, tin, copper, nickel, and iron were electrically exploded by the discharge current from a high-voltage capacitor. Three film thicknesses were investigated on substrates of glass and plexiglass at various energy levels in the range from 1 to 10 joule. Results of current and voltage measurements made with coaxial shunts and photographic observations made with a high-speed framing camera are presented.

29. Zernow, L., and Woffinden, G.,
CINEMICROGRAPHIC STUDY OF ELECTRICALLY EXPLODED METAL FOILS, Proceedings of the Sixth International Congress on High-Speed Photography, 17-22 September 1962, pp. 206-216.

An interest in the behavior of electrically exploded thin unsupported metal foils of tungsten and molybdenum has led to the current study. This paper will describe the cinemicrographic observations of such exploding foils.

The tungsten and molybdenum foils used in these experiments were ribbons 0.0003-inch thick and were 0.040-inch wide. Molybdenum in 0.090-inch width was also used. The effective ribbon length between the electrodes was approximately 0.5-inch width.

The foil holder was essentially a coaxial system with a window cut in the outer conductor for optical viewing. The foil itself was held by two small clamps along the direction of the center coaxial conductor.

A charged condenser is discharged through the foil. A coaxial type Park shunt is provided for making current-time measurements. Two switching systems were used.

In a few cascs, a 1.4-microfarad condenser was triggered with a spark gap (Lovotron). In most of the experiments a 2-microfarad condenser was triggered with a 5C22-hydrogen thyratron.

30. Zcrnow, L. and Wright, F. Jr., HIGH-SPEED CINEMICROGRAPHIC STUDIES OF ELECTRICALLY EXPLODED METAL FILMS, Proceedings of the Second Conference on the Exploding Wire Phenomenon, Boston, Massachusetts, 13-15 November 1961, Vol. 2, pp. 245-262.

Exploding metal films exhibit a striation phenomenon which has been previously reported. Studies of exploding films of aluminum on a glass substrate indicate that these striations are essentially perpendicular to the apparent current path and become visible early in the discharge as bright transverse regions from which aluminum is rapidly evaporated.

More detailed studies of the formation of these striations have now been carried out with the cinemicroscopic technique. At 25 x magnification and $1.2 \cdot 10^6$ frames per second an unusual polarized structure can be seen forming during the current flow at the site of artificial scratches on the film. These structures appear essentially identical with those formed in the absence of artificial scratches. These observations will be shown, and the effects of voltage and film thickness upon the striations will be commented upon.

AUTHOR INDEX

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Redstone Scientific Information Center Research and Development Directorate U. S. Army Missile Command Redstone Arsenal, Alabama 35809	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

EXPLODING FOIL TECHNIQUES: A BIBLIOGRAPHY

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

N/A

5. AUTHOR(S) (Last name, first name, initial)

Hoop, Herbert H.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
28 October 1965	21	30

8a. CONTRACT OR GRANT NO. N/A b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) RSIC 481 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AD ________

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Same as No. 1

13. ABSTRACT

This bibliography of "Exploding Foil Techniques" is an attempt to furnish basic exploding conductor information, and to locate literature on operating exploding foil systems, energy storage systems, design of power supplies and fast energy release systems. The listed documentation describes the use of exploding foil and films to produce hypervelocity plasmas, to accelerate particles, to create shock waves in matter, to create intense light pulses, and to compress magnetic fields. A number of pulse power energy storage systems are described.

DD FORM 1 JAN 64 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Exploding conductors, foils, wires Energy storage systems Energy release systems Hypervelocity plasmas Accelerated particles Magnetic fields						

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